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TECHNICAL NOTE

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CRASH-FIRE PROTECTION SYSTEM FOR A J57 TURBOJET ENGINE USING WATER AS A COOLING AND INERTING AGENT

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SUMMARY

A crash-fire protection system to reduce the likelihood of ignition of crash-spilled fuel that may be ingested by a modified J57 turbojet engine is described. This system included means for rapidly extinguishing the normal combustor flame and means for cooling and inerting with water the hot engine parts likely to ignite engine-ingested fuel.

Combustor flames were extinguished within 0.13 second after actuation of the system.

Hot engine parts were inerted and cooled by 16 gallons of water discharged through two separate spray systems. Several attempts were made to cool and inert the hot engine parts using only 14 gallons of water. Each attempt resulted in a local internal fire at 0.5 second after engine shutdown and lasted for 0.03 second. These local fires were not accompanied by an audible explosion nor did flames propagate out of the engine.

Since complete crash-fire protection called for extinguishing of internal flames without recurrence, the 14-gallon water system was considered inadequate.

Performance trials of the crash-fire protection system were conducted by bringing the engine up to maximum temperature, stopping the normal fuel flow to the engine, starting water discharge, and then spraying fuel into the engine to simulate crash-ingested fuel. No fires occurred during the trials with the 16-gallon water system, although fuel was sprayed into the engine from 0.3 second to 15 minutes after engine shutdown.

INTRODUCTION

As part of a continuing study of crash-fire safety for turbine-powered aircraft, the Lewis Research Center recently completed an evaluation of the crash-fire protection requirements for the interior of a modified J57 turbojet engine. This work followed an extensive laboratory and full-scale crash program with turbojet-powered airplanes, which showed that fuel spilled in a crash can be sucked into the engine with the intake air (ref. 1). This ingested fuel and air mixture may be ignited by combustor flames and by some of the hot metal of the engine interior. The resulting flames issue from the engine inlet and tailpipe and ignite other fuel spilled around the crashed airplane to cause the main fire.

The full-scale crash program showed that combustible spillage could be simulated for a turbojet engine on a test stand. Therefore, the crash-fire hazard presented by the jet engine was assessed by test-stand studies.

In the full-scale crash research program, which was conducted with turbojet-powered airplanes, the ignition of fuel ingested by the engines was prevented by extinguishing the normal combustor flames rapidly and by cooling and inerting the dangerously hot metal parts of the engine immediately upon crash. Water was the cooling and inerting agent.

Turbojet engines with only one turbine and a single-spool compressor of low compression ratio (approximately 5) were used in the full-scale crash program. This report discusses the results of an experimental evaluation of a crash-fire protection system for turbojet engines that have two-spool compressors and multistage turbines. The high compression ratio of this engine (approximately 11 compared with approximately 5) produces high wall temperatures. Ingested fuel is heated to higher temperature and will, therefore, ignite more readily. The multistage turbine rotors present a larger surface area and greater mass and heat capacity than the single turbine and, consequently, ingested fuel is more likely to become ignited.

For this study, a J57 engine was modified to resemble the later model JT3C-6 turbojet engine used in present-day commercial jet aircraft. These modifications consisted primarily of changes in the components affecting internal airflow characteristics and deletion of obsolete components.

ENGINE

The J57-P-3 turbojet engine (figs. 1 and 2) is a continuous-flow gas-turbine engine incorporating a two-spool axial-flow compressor, an eight-unit semiannular combustor, and a split three-stage turbine. The multistage axial compressor consists of a nine-stage low-pressure unit and a seven-stage high-pressure unit. The low-pressure compressor is connected by a through shaft to the second- and third-stage turbine wheels and the high-pressure unit is connected independently by a hollow shaft to the first-stage turbine wheel.

For crash-fire protection considerations, the principal difference between the J57-P-3 turbojet engine and a commercial JT3C-6 turbojet engine is the internal cooling-airflow characteristics. In order to reduce the possibility that these internal cooling-airflow differences might affect the final arrangement of the crash-fire protection system, the J57-P-3 engine was modified to approximate the internal cooling airflow of the JT3C-6 engine. These modifications consisted of the following:

(1) Four 9/16-inch holes, equally spaced, were drilled in the front hub of the high-speed compressor (fig. 2, item I, and fig. 3(a)).

(2) One of two compressor bleed valves was removed and its opening closed (fig. 2, item II, and fig. 3(b)).

(3) Sixty-four equally spaced 1/4-inch holes were drilled in the spacer located between the twelfth- and thirteenth-stage rotor blades of the high-speed compressor (fig. 2, item III, and fig. 3(c)).

(4) All tie bolt holes in the rear face of the high-speed compressor were blocked (fig. 2, item IV, and fig. 3(d)).

(5) All holes in the rear hub of the high-speed compressor were closed (fig. 2, item V, and fig. 3(d)).

(6) Holes in the spacer lying between the second and third turbine wheels were blocked (fig. 2, item VI, and fig. 3(e)).

(7) Heat shields attached to the fuel-manifold assembly were removed (fig. 2, item VII).

(8) The circular-screen assembly upstream of the fuel nozzles was removed (fig. 2, item VIII).

(9) The diaphragm was removed from the turbine nozzle case (fig. 2, item IX).

These changes resulted in the internal airflow passages shown schematically in figure 4. During normal engine operation, this airflow aids in cooling engine components; but under crash circumstances, combustibles entering the engine inlet are routed via these passages to components of high ignition potential. However, these same passages may also be utilized to distribute cooling and inerting media to the hazardous ignition surfaces.

CRASH-FIRE PROTECTION SYSTEM

The crash-fire protection system for the interior of the engine comprised an engine fuel-manifold shutoff and drain system, which quickly extinguished the combustor flames, and two types of water-spray systems, which cooled and inerted the dangerously hot metal surfaces. While hot surfaces were being cooled to safe temperatures, the steam generated by evaporation of water from these hot surfaces provided an inert atmosphere, which aided in suppressing ignition.

Coolant quantities and points of water application within the engine (fig. 5) were determined by a test-stand engine study, following the procedure described in reference 1.

The crash-fire protection system is described in the following paragraphs.

Fuel Shutoff and Drain System

During a normal engine shutdown, flames persist in the combustor liners for about 18 seconds after the throttle has been closed manually. These flames are fed by fuel remaining in the manifold after shutdown that normally drips from the lower nozzles until the fuel manifold is drained. The flame supported by the dripping fuel can instantly ignite crash-spilled fuel ingested by the engine. These flames also will ignite combustibles over greater limits of mixture, pressure, and velocity than will the hot engine surfaces. Therefore, they should be eliminated as quickly as possible.

In the J57 engine, the combustor flames were eliminated by providing for rapid fuel shutoff and draining of the fuel manifold. The fuel was shut off by a pneumatically operated valve installed in the fuel line between the engine fuel-control unit and a modified pressurizing and dump valve as shown in figure 6. Simultaneously, the manifold drain valves (fig. 6) and the modified pressurizing and dump valve opened and vented the fuel manifold overboard. The combustor air pressure, available at the instant the fuel shutoff valve closed, then reversed the fuel flow in the nozzles and manifold through the overboard fuel drains. The combustor flame was extinguished in 0.23 second by this method.

Water-Spray Systems

The water-spray systems that inert and cool the hot engine parts must be designed to take into account the heat dissipitation properties of the various engine parts. Thin metal parts such as combustor liners, transition liners, exhaust ducts, and turbine blades have large ratios of surface to mass and may be cooled quickly. Massive parts such as turbine rotors and support structures have smaller surface-mass ratios and cannot be cooled rapidly. For this reason, two types of water-spray systems using 16 gallons of water were used to cool and inert the hot surfaces within the engine.

A short-duration discharge of water suppressed ignition of the thin structures around the main gas stream and also decreased the time that flames remained in the combustors from 0.23 second to 0.13 second after engine shutdown. These very hot thin structures cool rapidly, and a short duration discharge is adequate. However, the surface area is large and a high flow rate is needed. The short-duration discharge system is subsequently referred to as the combustor system.

A slow-flow, long-duration discharge of water inerted and cooled (1) the rear compressor bleed-air collector case; (2) the outer structure between the eight outlets ducts of the turbine-nozzle assembly; (3) the inner turbine casing; and (4) the front and rear surfaces of the turbine-rotor assembly. Because these parts are massive, it was necessary to inert and cool them until the internal heat was insufficient to reheat the surfaces to ignition temperature after the water spray had stopped. This long-duration water system is subsequently referred to as the turbine system. Both water-spray systems are shown in figure 5 and are described in detail in the following paragraphs.

Combustor system. - The water from this system inerted and cooled the combustor-liners and the structures enclosing the main airstream.

The combustor system consisted of eight spiral nozzles, one located in front of each combustor liner as shown in figure 7. These nozzles have two spray-cone patterns, an outer, wide-angle cone and a narrower inner cone. These combine to give a full-cone effect, which produces an atomized water spray at relatively low pressures. The rated discharge of each nozzle was 26 gallons per minute at a pressure of 100 pounds per square inch. Advantage was taken of the high-velocity inlet airflow to further atomize the water and distribute it over the combustor liner surfaces by installing the nozzles so that the water discharged upstream against the airflow (ref. 7).

A total of 8.5 gallons of water was discharged in 5 seconds from a single tank pressurized with nitrogen to 385 pounds per square inch gage. The pressure and volume of the propelling nitrogen gas and the discharge-nozzle orifice areas were selected to give the desired fast-flow, short-duration discharge.

To facilitate the measurement and future duplication of the water discharge, the data shown in figure 8 were obtained with the combustor system discharging to atmospheric pressure (engine not operating) rather than to the declining combustor pressure of the coasting engine. Since combustor pressure was 135 pounds per square inch at shutdown time, the initial water discharge pressure (250 lb/sq in.) was increased by this amount in performance evaluation runs.

Filling the dry passages between the water-reservoir valve and the discharge nozzles with water expends some of the initial propelling-nitrogen-gas pressure, thus reducing the pressure available at the nozzles and also increasing the time needed to fill the lines. In order to avoid large dry-passage volumes, the line lengths between valve and discharge nozzle were kept to a minimum as shown schematically in figure 9. Dry volumes in production water spray systems should be restricted to those used in this experimental version. Reducing dry volumes decreases the lag time in delivering water to the critical parts of the engine, thereby shortening the hazard time immediately after crash.

Turbine system. - The turbine system consisted of four subsystems. One of the subsystems sprayed water into the air cavity of the rear compressor bleed air collector case. One subsystem sprayed water on the outer structure between the eight outlet ducts of the turbine-nozzle assembly. Another subsystem sprayed water into the inner turbine nozzle. The fourth subsystem sprayed water on the front and rear surfaces of each of the three turbine wheels. Figure 10 is a schematic diagram of the turbine-system subsystems, which are designated compressor bleed, outer turbine nozzle, inner turbine nozzle, and turbine rotor. Surfaces that were not sprayed directly by these subsystems were inerted and cooled by the steam generated from water sprayed on adjacent surfaces.

A total of 7.5 gallons of water was discharged in 27 seconds from two tanks pressurized initially to 255 pounds per square inch gage with nitrogen gas. The pressure and the volume of the nitrogen gas and the nozzle orifice areas were selected to give the desired long-duration discharge. The water-pressure decay with time for the combined turbine system, when discharged to atmospheric pressure (engine not operating), is shown in figure 11. As with the combustor system, the initial reservoir pressure was corrected to account for pressure existing in the water-discharge area.

Compressor-bleed subsystem: The annular chamber running circumferentially around the engine and formed by the rear compressor case and the compressor bleed air collector case (fig. 5) was cooled and inerted by water from eight 125° flat-spray-angle nozzles. Each nozzle had a 0.028-inch orifice and a rated discharge of 0.18 gallon per minute at a pressure of 60 pounds per square inch. These nozzles were placed so that the water spray impinged on the hot surfaces at the rear of the annular chamber. Details of the nozzle installation are shown in figure 12(a). A small amount of water was sufficient to cool these surfaces, because only the last two compressor stages heat the adjacent surfaces to a temperature that could ignite ingested fuel.

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Outer-turbine-nozzle subsystem: The portion of the turbine-nozzle surfaces not protected by the upstream combustor system were cooled by water from eight, 80°-solid-cone, spray nozzles. These nozzles were mounted between each of the eight outer turbine-nozzle surfaces as shown in figure 12(b). Each nozzle had a rated discharge of 0.67 gallon per minute at a pressure of 100 pounds per square inch.

Inner-turbine-nozzle subsystem: Two sets of nozzles were used to cool and inert the surfaces of the first-stage turbine-nozzle inner-case assembly. The first set contained five, 119°-flat-spray-angle nozzles located circumferentially on the turbine front bearing and outer-seal support as shown in figure 12(c). These nozzles were so aimed that the water jets would strike and wash over the skin of the turbine-nozzle inner case and the front face of the first-stage turbine disk. Each nozzle had an equivalent orifice of 0.052 inch and a rated discharge of 0.63 gallon per minute at 100 pounds per square inch. The second set contained five 47°-flat-spray-angle nozzles, which were mounted on the first-stage turbine inner-seal support as shown in figure 12(d). These nozzles directed a finely atomized water spray, through six holes $\left(1\frac{1}{8}\text{-in. diam.}\right)$ located in the rim of the rear compressor-drive turbine shaft, which cooled and inerted the base of the first-stage turbine wheel. In addition to cooling and inerting the base of the first-stage turbine rotor, the turbine cooling air carried water mist and steam to spaces behind the first turbine wheel and in front of the second-stage turbine stator (fig. 12(d)) and helped to inert these zones. Each nozzle in the second set had an equivalent orifice of 0.072 inch and a rated discharge of 1.26 gallons per minute at a pressure of 100 pounds per square inch.

Turbine-rotor subsystem: The separation space between the turbine-rotor and each stage of the turbine-stator assemblies formed six annular chambers running circumferentially around the engine as shown in figure 12(e). A slow flow of water over a long interval cooled the surfaces enclosing these chambers while providing inerting steam around their surfaces.

Water was discharged into each annular chamber from three 117°-flat-atomizing spray nozzles installed on the rear face of the first-stage turbine-stator-seal assembly, on the front and rear faces of the second- and third-stage turbine stators, and on the turbine-exhaust inner duct. The rated discharge of these nozzles was 0.95 gallon per minute at a pressure of 100 pounds per square inch. Figure 12(e) shows the location of these nozzles in each of the six annular chambers. The nozzles were approximately parallel to the turbine-rotor surface and directed against the direction of turbine wheel rotation.

Two small metal tabs were spot-welded to the front and rear surfaces of each of the three turbine rotors (fig. 13). These tabs assisted in dispersing the water spray throughout each chamber to cool the turbine-stator surfaces as well as the turbine rotors. In addition to cooling and inerting the surfaces of the turbine wheel and the stators, the turbine cooling air carried the atomized water mist and steam to the roots of the turbine blades and helped to water-cool these surfaces.

PERFORMANCE TRIALS

Effectiveness of the crash-fire protection system was evaluated by subjecting the modified J57 engine mounted on a test stand to severe crash fuel-spillage conditions. This simulation was accomplished by installing fuel-spray equipment in the engine inlet and tailpipe to produce the most hazardous conditions of crash-generated fuel mist and liquid fuel spillage described in reference 1. In a crash, the fuel mist can be carried through the engine by the inlet airflow. Liquid fuel may also enter the entire inlet or tailpipe by running along inclined airplane surfaces after the airplane is no longer moving and the engine has stopped rotating.

For this evaluation, the engine was mounted in a test stand located beneath the surface of the ground as shown in figure 14. All engine controls and data recorders were housed in a control shack located some distance from the test stand to reduce the hazard to operating personnel in the event destructive explosions within the engine were produced by the ingested fuel.

Engine conditions were established that corresponded to those that would exist in a crash on takeoff. A crash on takeoff represents the most severe crash-fire hazard because the engine temperatures are highest under these conditions. To simulate take-off conditions, the test stand engine was operated at a maximum exhaust-gas temperature of 1200° F until the temperature of the internal metal parts reached equilibrium. Then, at a moment that corresponded to airplane impact with the ground, the fuel flow to the engine combustors was stopped and the water spray system was actuated.

At 0.3 second after the fuel flow to the engine combustors was stopped, JP-4 fuel was sprayed into the engine inlet to simulate ingestion of crash-spilled fuel. Fuel spray quantities were varied continuously with decreasing inlet airflow to provide a fuel-air ratio approximately twice stoichiometric during the first 10 seconds after engine shutdown. This fuel-air ratio was used because of the ease with which it can be ignited. After the 10-second interval, the twice stoichiometric spray was replaced by 4- to 5-second duration pulses of atomized fuel directed into the engine inlet and exhaust. In the exhaust section, fuel impinged on the rear turbine exhaust struts and the rear turbine rotor. The pulsed fuel spray covered a range of fuel-air ratios from too-lean to too-rich. This pulsed fuel spray was actuated at 15-second intervals during the period from 10 seconds to 3 minutes after shutdown. During the 3- to 6-minute period, fuel pulses were actuated every 30 seconds. Fuel was sprayed in pulses every minute between 6 to 15 minutes after engine shutdown.

The fuel selected for the sprays was JP-4 grade because it is the fuel intended for use by commercial airlines in aircraft equipped with the J57 engine. This fuel has one of the lowest spontaneous ignition temperatures of all the combustible liquids carried in turbojet aircraft.

FIRE DETECTION

Fires that resulted from inadequate fire protection in some chambers of the engine were often difficult to detect. Visible flame at the exhaust or inlet or an audible explosion indicated fire within the engine. However, a fire can occur inside the engine without these indications. Since for optimum crash-fire protection all internal flames must be extinguished, another method of detecting local internal fires had to be devised. Motion pictures taken through windows in the combustor housing provided a sensitive and reliable means of detecting these local internal fires. These windows are shown in figure 1. The longitudinal view taken through the three windows at 32 frames per second also indicated the direction of flame propagation and thus pointed to the sources of ignition. Flames of less than 0.1-second duration were photographed.

Thermocouple fire detectors were useful for detecting flame propagation in other locations inside the engine. However, they were not capable of detecting brief flashes of flame that may be present when almost enough water to prevent fire was used.

Pressure pulses within the engine caused by fire or explosions were a useful supplement to the other methods of fire detection in both preliminary and final performance trials. Although pressure pulse-fire detectors were more sensitive than the thermocouple fire detectors, they were not as positive for detecting brief flames in the engine as motion pictures taken through the windows.

GENERAL REMARKS

In a crash, fuel mists in combustible concentrations with air may be ingested through the engine inlet and ignited within the engine. Fuel in mist form is extremely hazardous, but it seldom persists around the crashed airplane for more than 15 seconds. Beyond this 15-second period, fuel spillage is usually in liquid form, thereby reducing the fire hazard as described in references 1 and 2. It is therefore important that a fire-protection system prevent ignition at least over the period of maximum hazard, although an optimum system would provide protection over the entire ignition-hazard period.

The stringent specifications of the crash-fire protection system described herein required 16 gallons of water, which was discharged according to the schedule shown in figure 15. Although all water was expended from the system in 27 seconds, fire was prevented within the engine for at least the 15 minutes of fuel spray. From these data it is difficult to predict the effect of decreasing the water quantity.

However, the quantity of water could probably be reduced by decreasing the time during which ignition is suppressed. If ignition is to be prevented only during the major hazard period, the duration of water flow can be decreased from 27 to 15 seconds. Figure 15 indicates that 3.5 gallons of water may be eliminated. However, this reduction in quantity may result in insufficient cooling of the massive engine components and, therefore, ignition of the liquid fuel present in the later phases of the crash.

Performance trials made with only 14 gallons of water resulted in a local fire within the engine at approximately 0.5 second after engine shutdown. These local flames persisted for 0.03 second, but did not result in an audible explosion nor did flame propagate from the engine. In view of the fact that a "no-flame" criterion had been adopted, a 14-gallon water system would be considered inadequate.

In designing a production-engine system, some changes in detail from the systems described are to be expected because of manufacturing necessity and engine operation. The geometry of the nozzle installations can probably be modified in a minor way if the distribution and discharge histories of water in the various systems are essentially unchanged. On the basis of experience gained in the experimental program, it is felt that minor variations in nozzle angles and spray patterns will not produce major changes in the effectiveness of the system. Consequently, it is believed that the system will not require precise duplication in its manufacture. When major modifications are involved, it would be desirable to subject the modified protection system to trials similar to those described herein.

The integrity of the system must not be allowed to deteriorate during its flight life if it is to protect fully against crash ignition in the most severe exposures to crash-spilled fuel. Experience obtained during the preliminary studies on the J57 engine showed that minor damage or partial blockage of individual nozzles do not result in a complete loss of crash-fire protection. When the engine was disassembled prior to the final proof runs, several water lines to individual nozzles were found broken. This condition prevented the nozzles from obtaining a full water supply or a full spray pattern, yet no fires occurred in performance trials of the 16-gallon water system.

When this engine is installed in an airplane, additional studies will be needed to determine if the exhaust ducting, such as a noise suppressor, and the exterior of the engine can ignite crash-spilled fuel. The need for an exterior fire protection system will depend largely on the ventilation provided over the engine exterior and the length of the exhaust duct that may be used. These hot surfaces should be subjected to fuel-spray trials in the airflow and temperature environment provided by the nacelle in which the engines are installed. Since the interior water systems can help cool the exterior surfaces by conduction, they should be used when making these studies. If protection is required for the exhaust ducting, the methods described in reference 1 may be used. In the method described in this reference, the hot exterior exhaust duct is covered with a waffle-like grid of fine wire screen. Manifolds, located between the screen and the exterior exhaust duct surface, spray water onto the hot surfaces. The screen tends to hold the water in close contact with the hot surface and promotes cooling.

A complete aircraft-fire protection system will also require the de-energizing of ignition sources not associated with the engine by the methods described in reference 2. These ignition sources include other hot surfaces, such as those associated with auxiliary powerplants and combustion heaters, and the sparks and arcs produced when electric power networks and equipment are destroyed.

A suitable method of initiating the action of these crash-fire protection systems is also needed. In a manually operated system, the actuation switch must be readily accessible for crash operation but safe from inadvertent actuation in normal flight. An entirely automatic system actuated by events leading to fuel spillage in a crash also has been proposed in reference 3. Such automatic systems can be considered for airplane use only after highly reliable equipment has been developed and service tested.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, December 22, 1959

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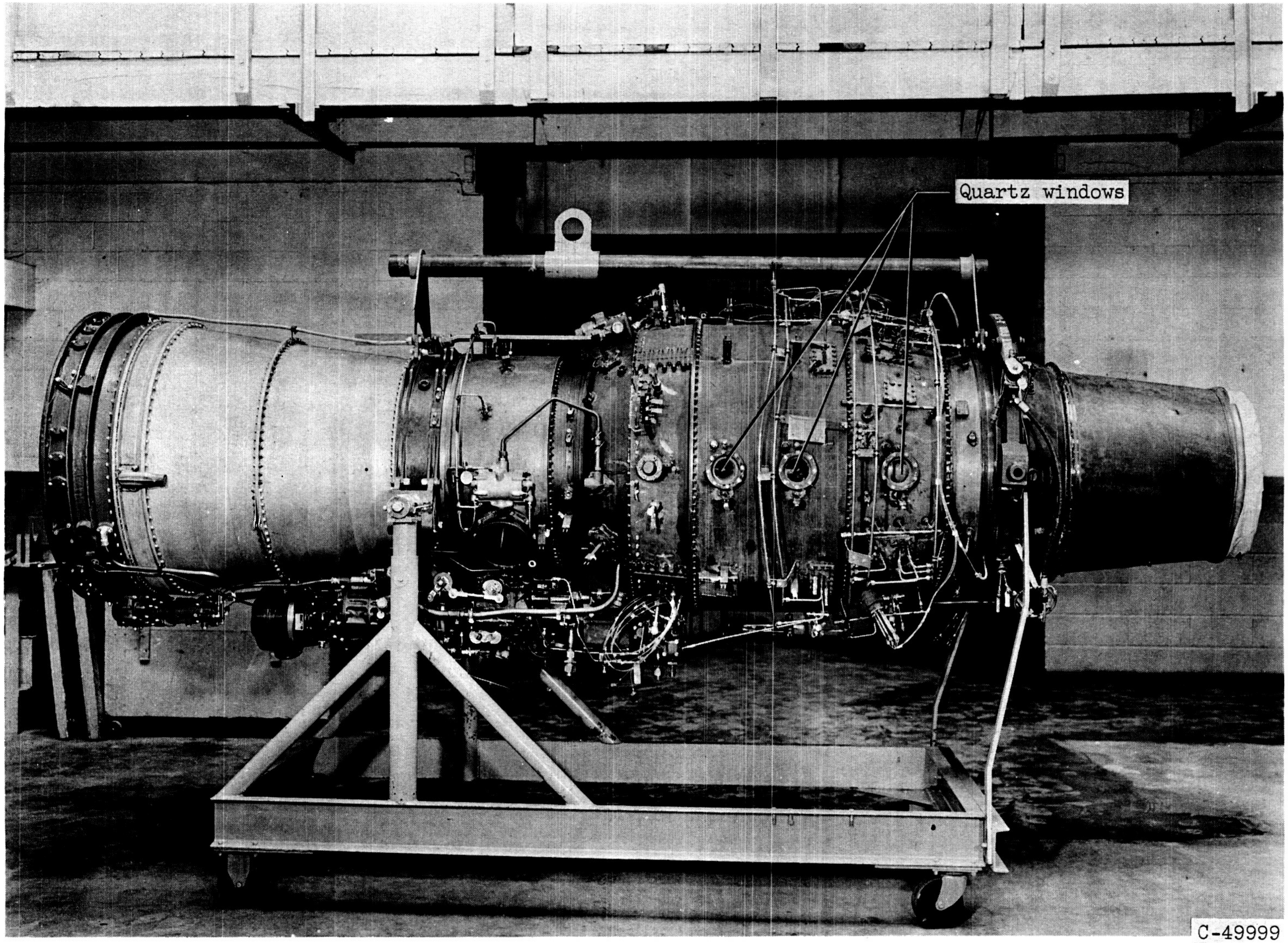

Figure 1. - Engine used in crash-fire protection studies.

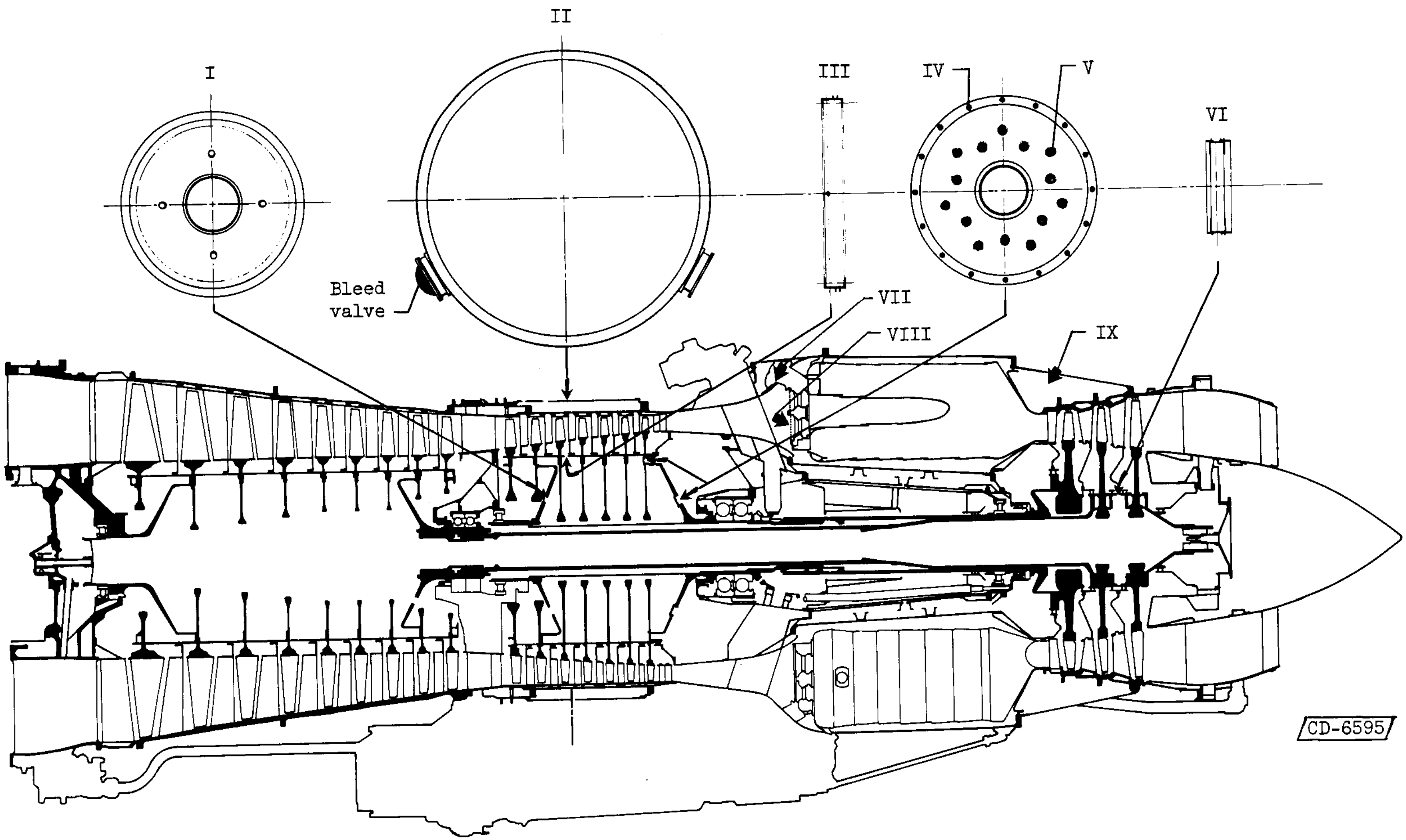

Figure 2. - Modifications incorporated into J57 engine.

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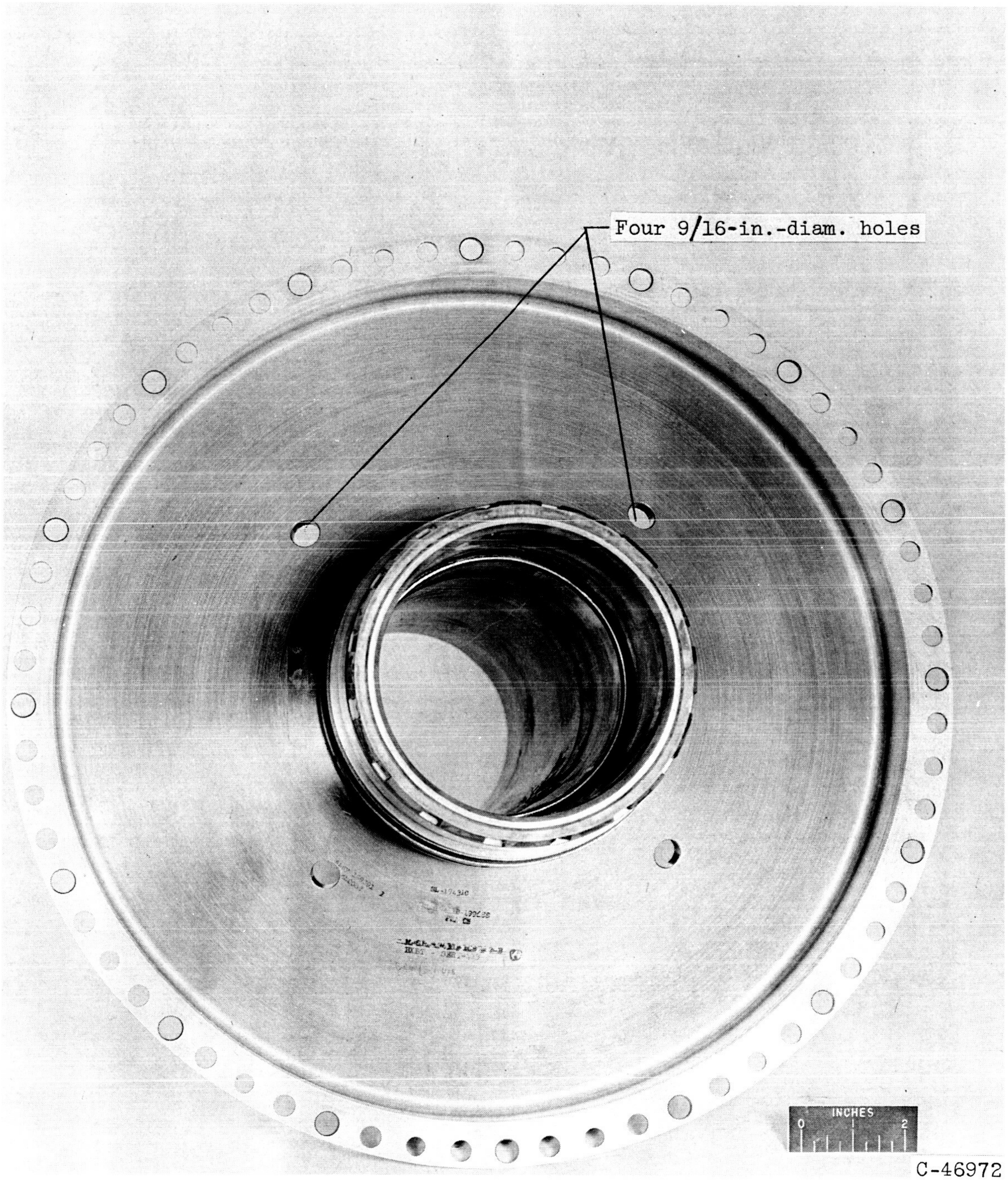

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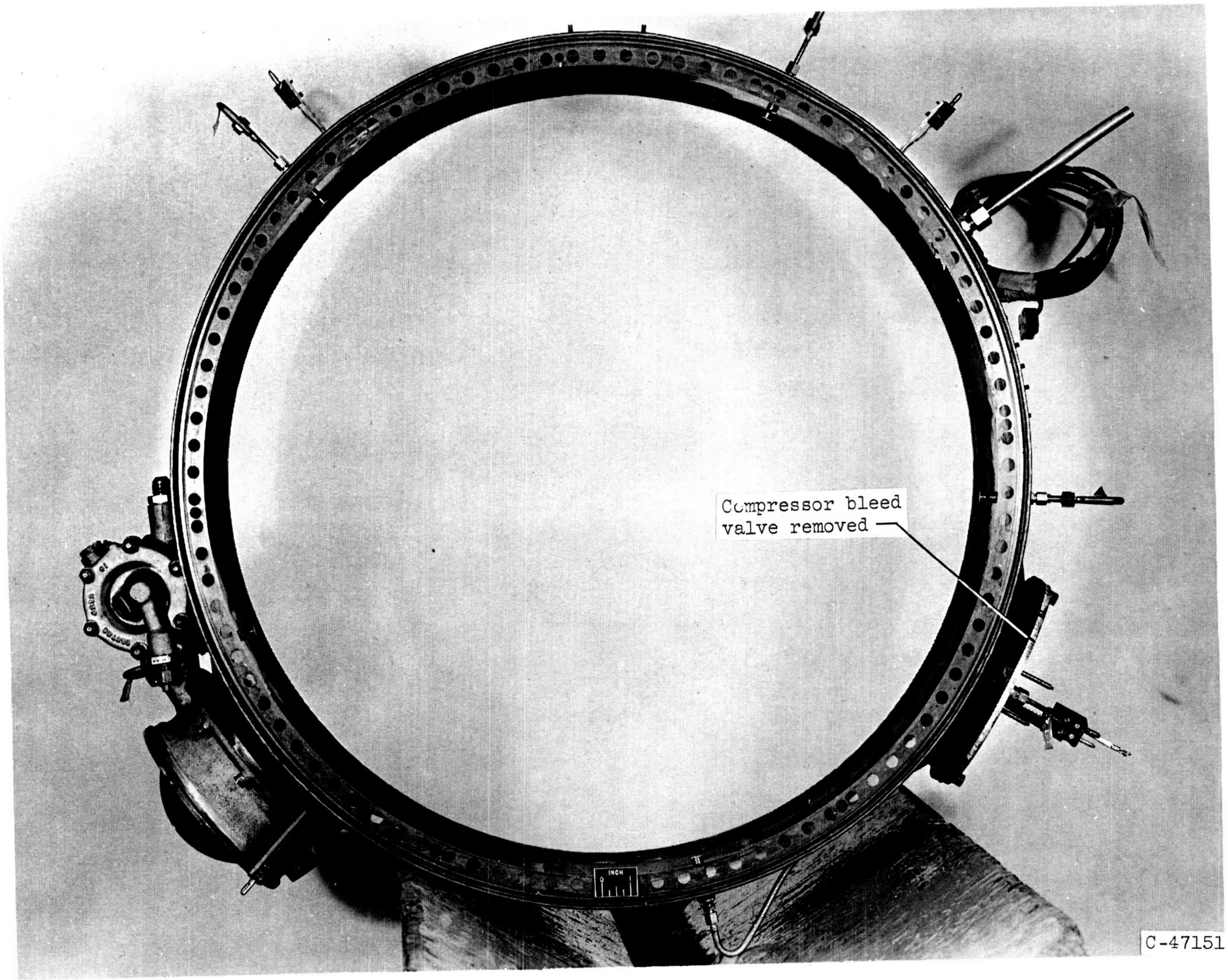
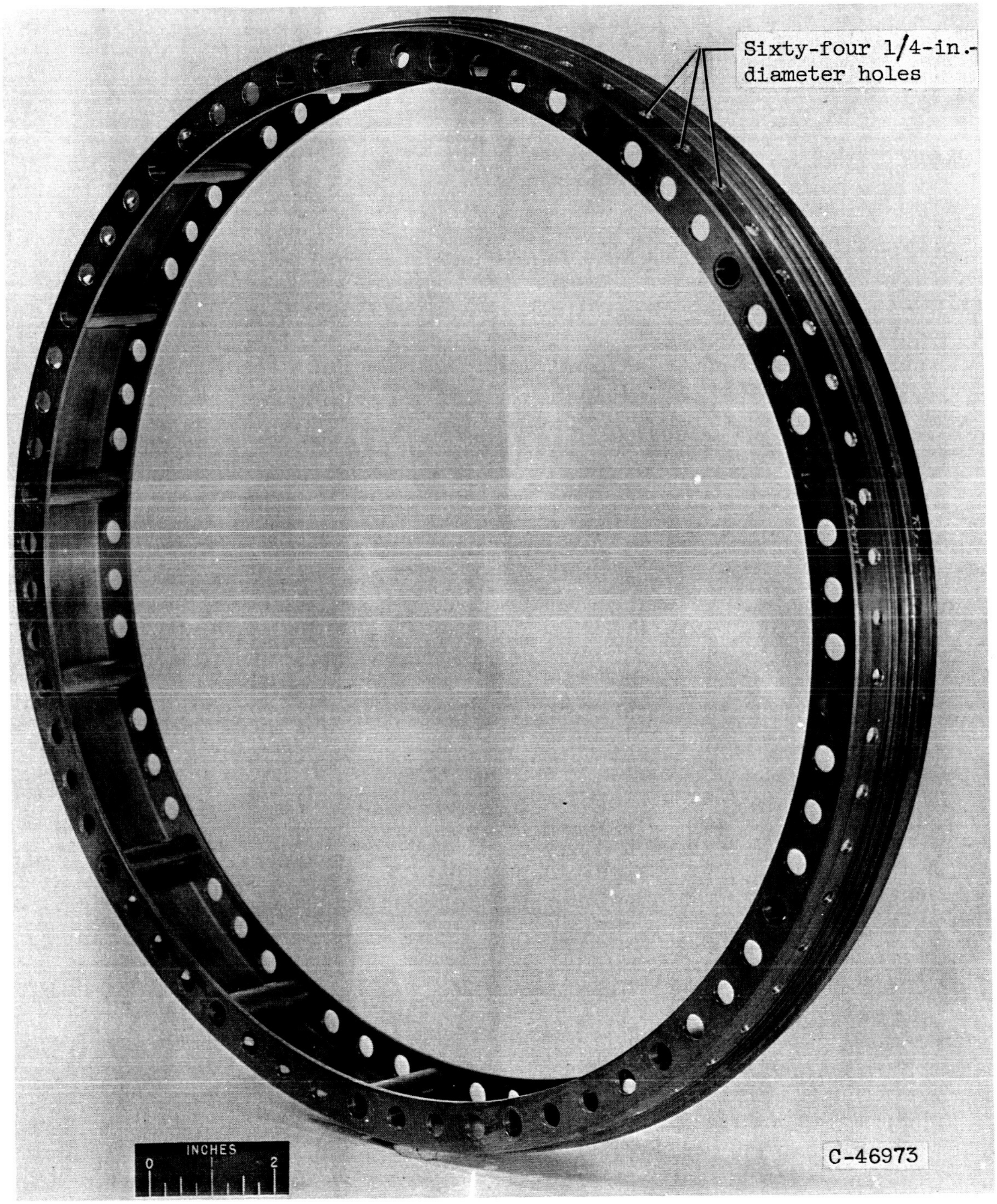
(a) Holes drilled in front hub of high-speed compressor (item I).

Figure 3. - Modifications incorporated into various components of J57 engine.



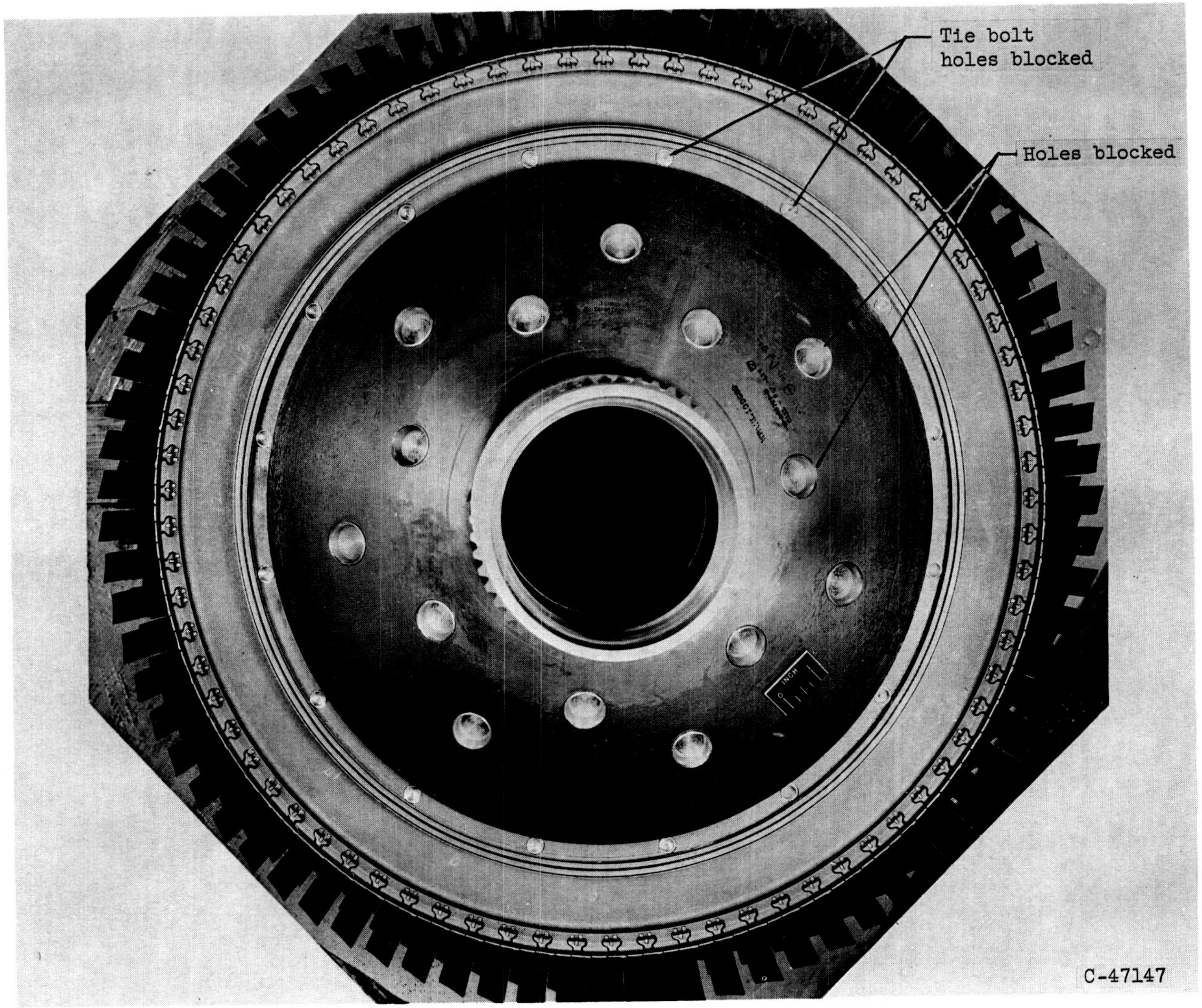
(b) Compressor bleed valve removed and opening blocked (item II).

Figure 3. - Modifications incorporated into various components of J57 engine.



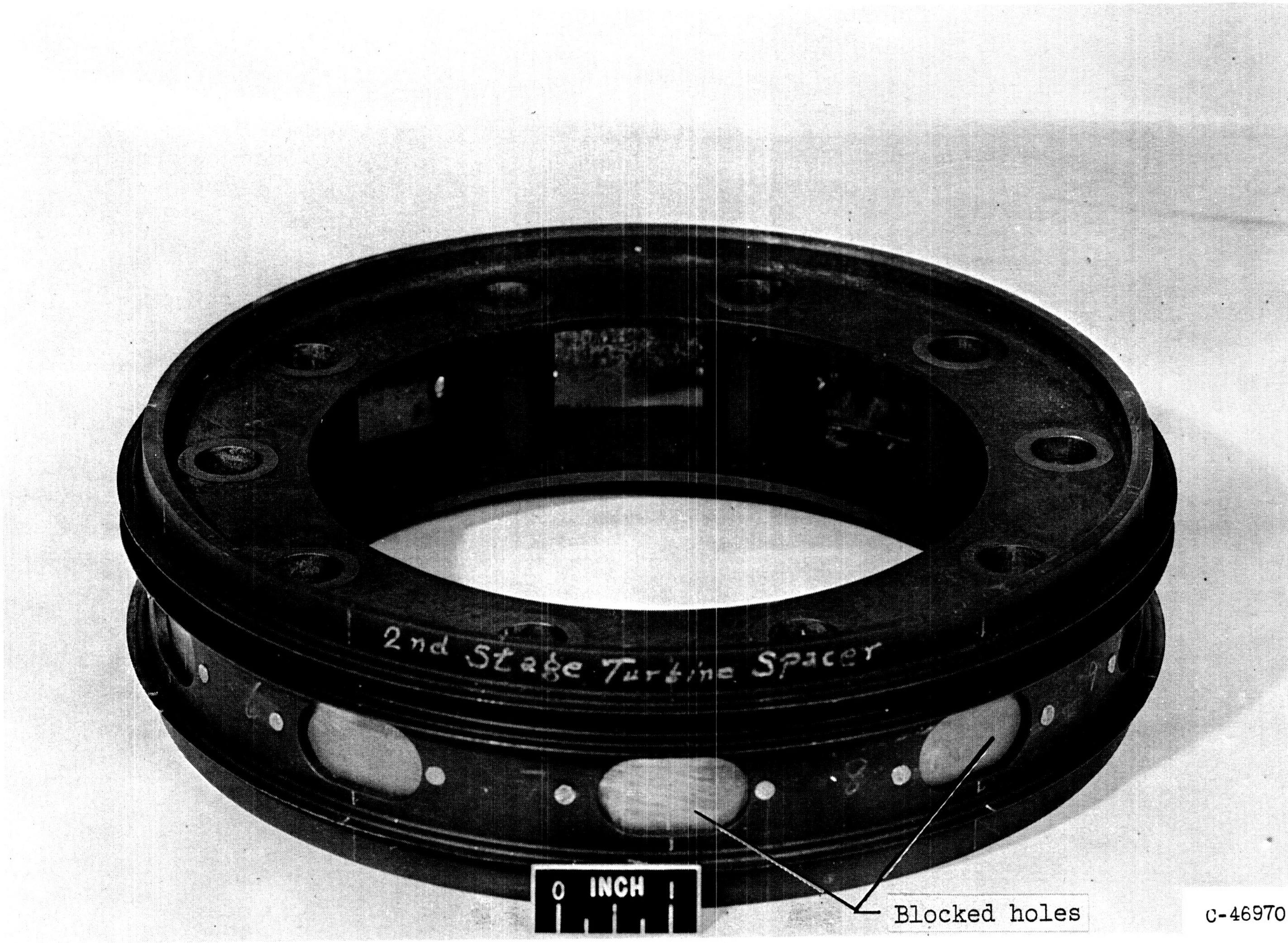
(c) Holes in spacer (item III).

Figure 3. - Modifications incorporated into various components of J57 engine.



(d) Holes blocked in rear hub of high-speed compressor (items IV and V).

Figure 3. - Modifications incorporated into various components of J57 engine.



(e) Blocked holes in second-stage turbine spacer (item VI).

Figure 3. - Concluded. Modifications incorporated into various components of J57 engine.

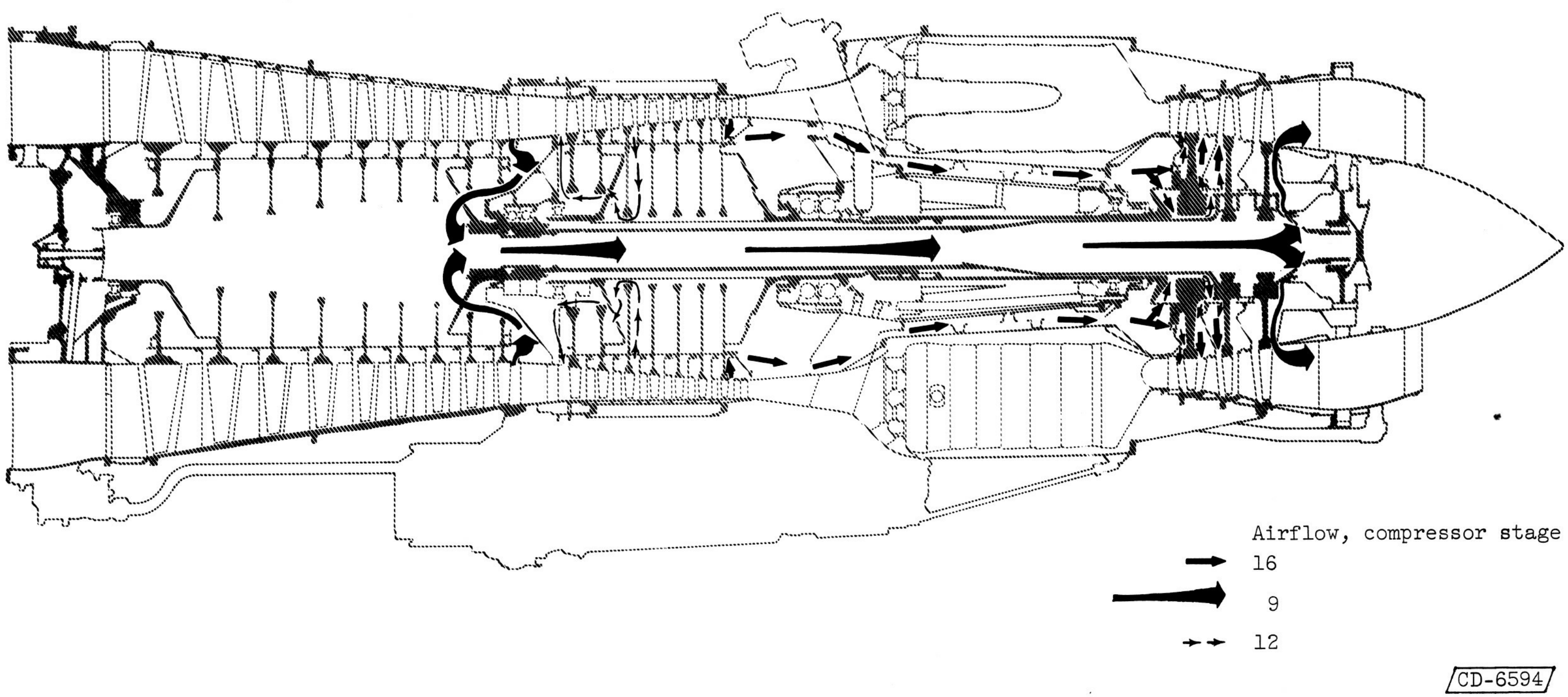


Figure 4. - Internal cooling airflow passages in modified J57 engine.

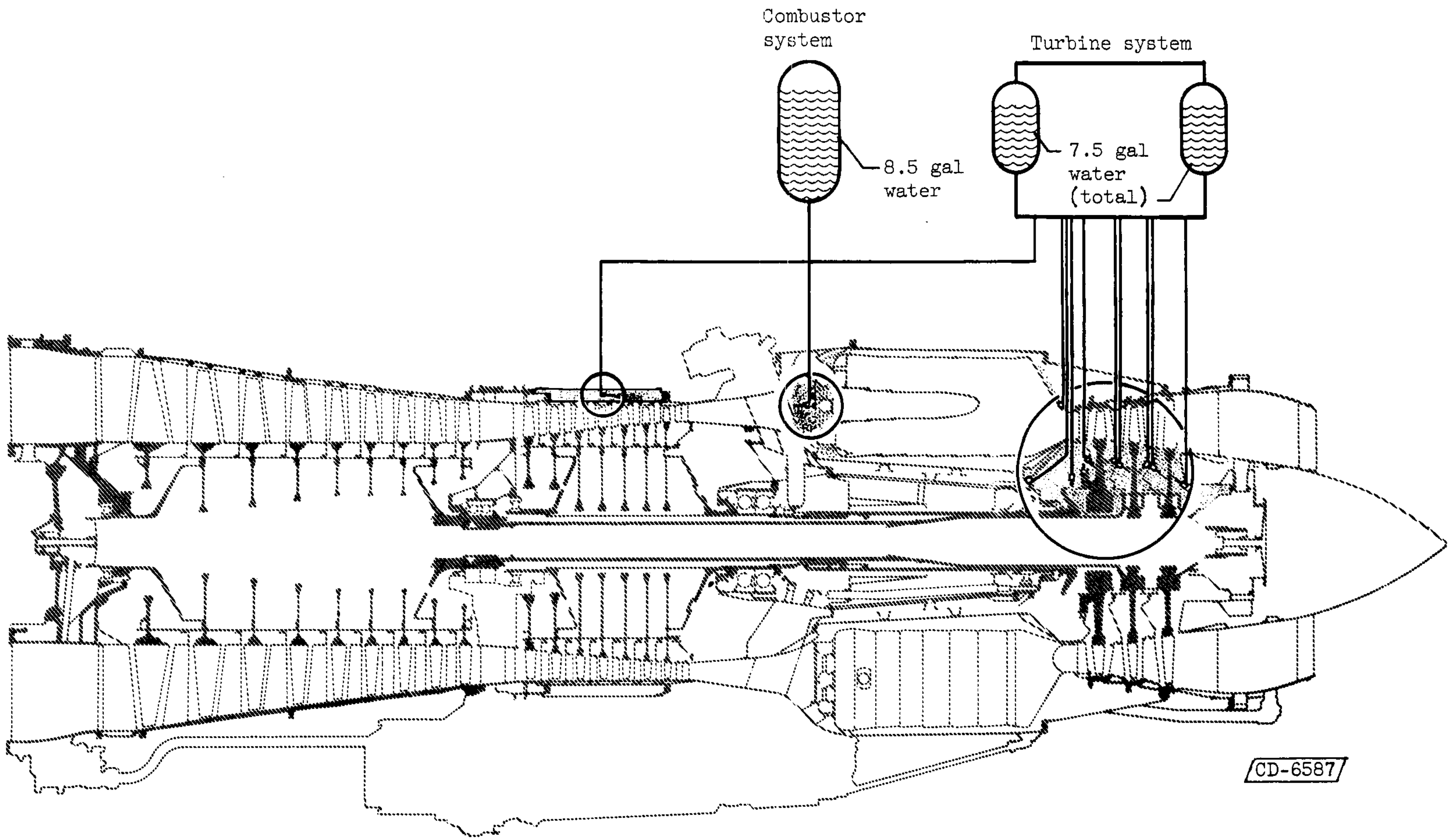


Figure 5. - Crash-fire protection system for J57 turbojet engine.

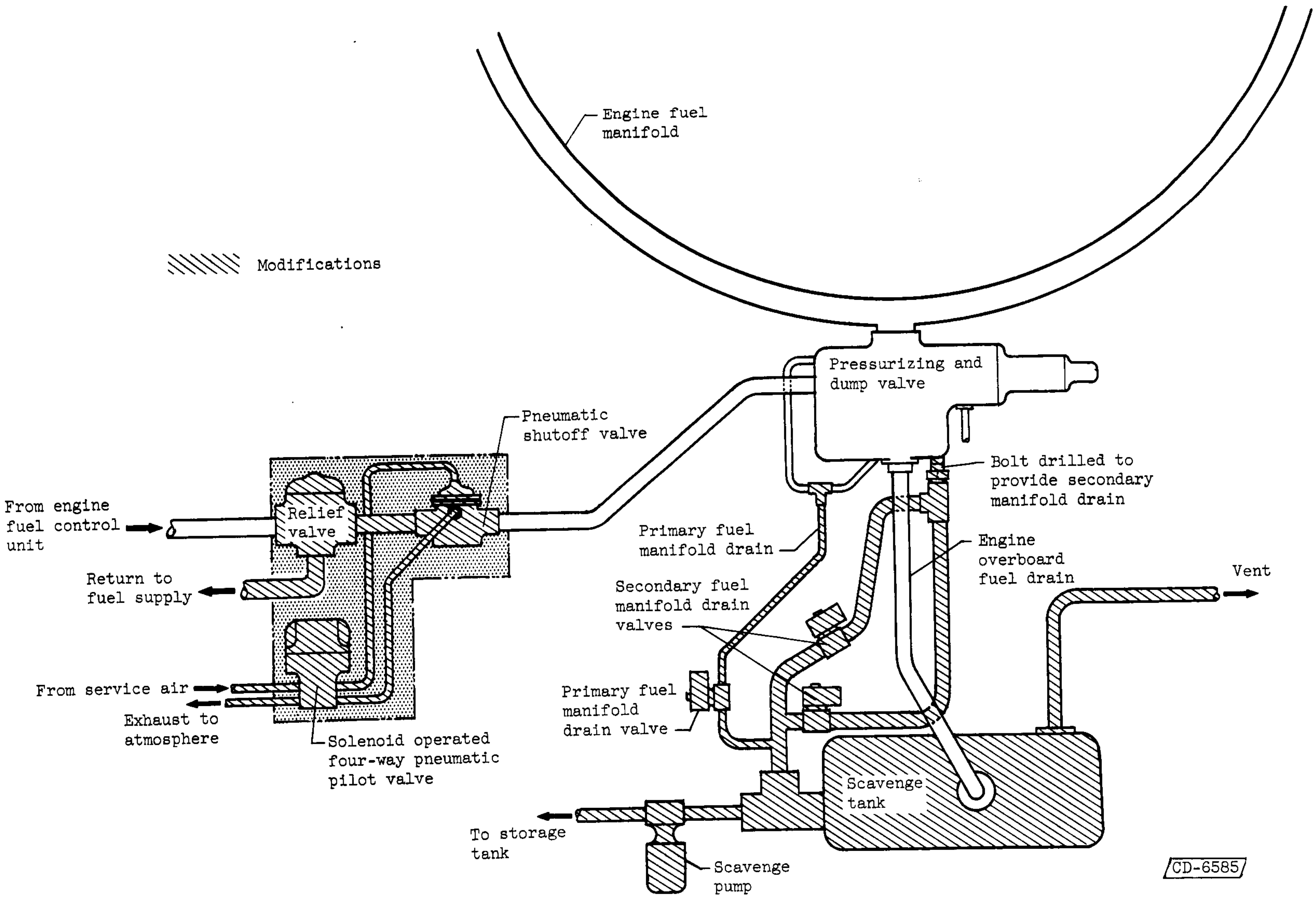


Figure 6. - Schematic diagram showing fuel shutoff and drain system in J57 engine crash-fire protection system.

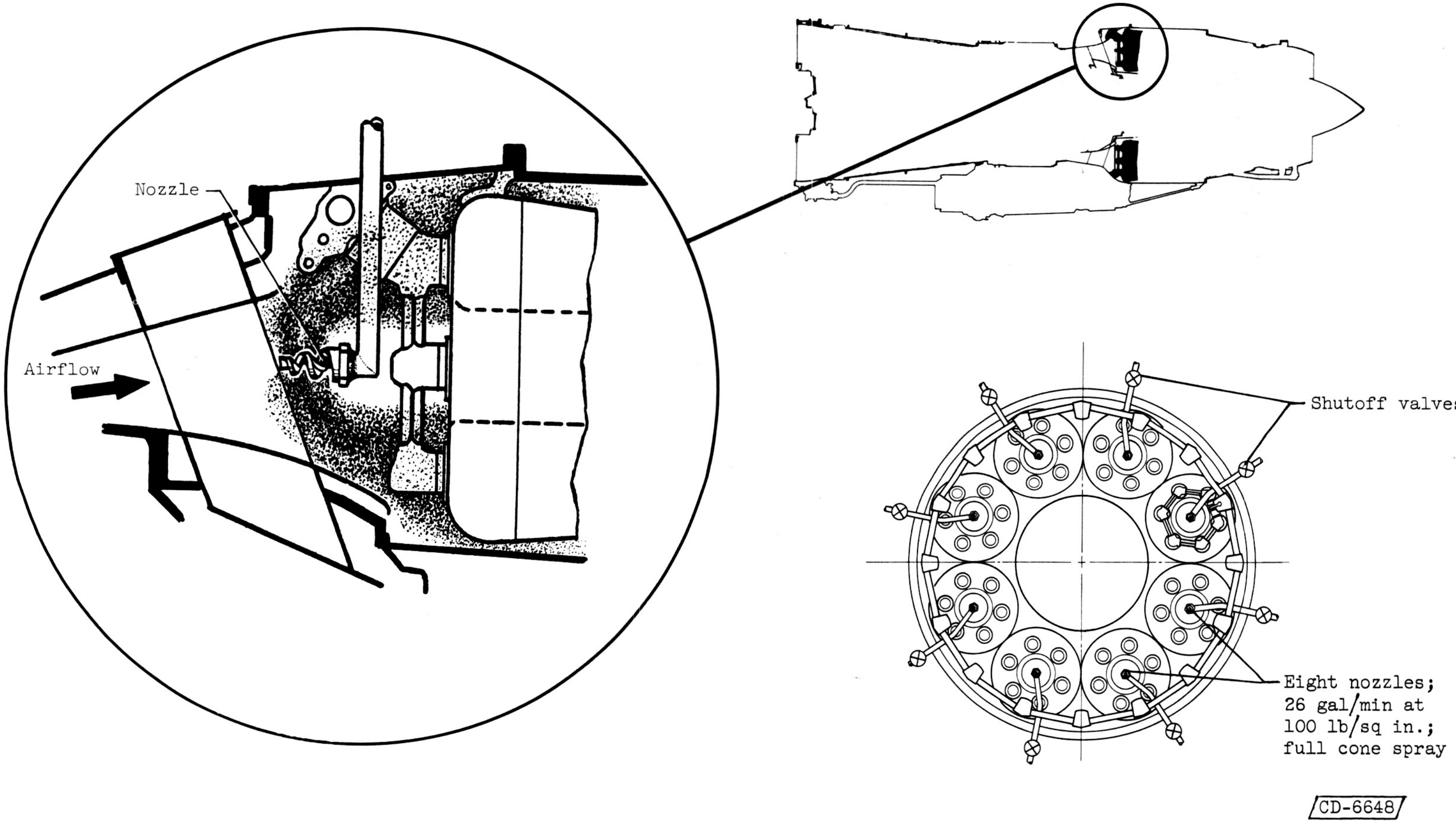


Figure 7. - Combustor system nozzle location in J57 engine.

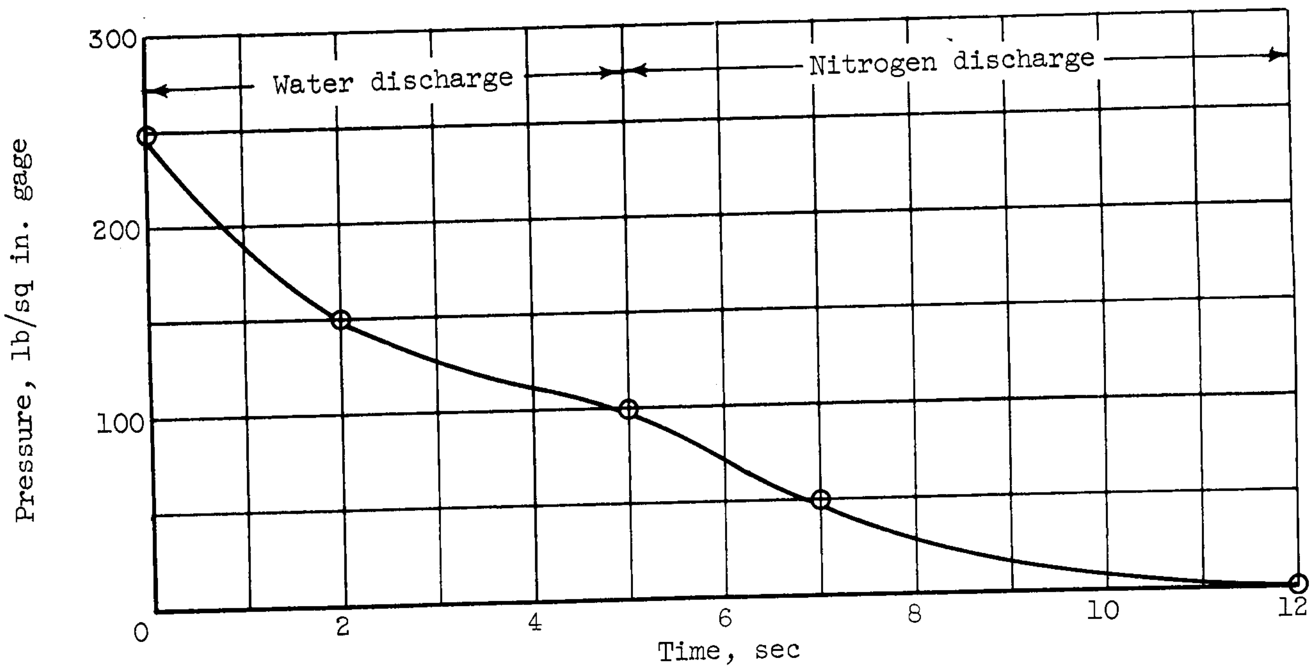


Figure 8. - Time history of crash-fire-protection combustor system pressure decay when discharged to atmospheric pressure (engine not operating). Water discharge, 8.5 gallons in 5 seconds.

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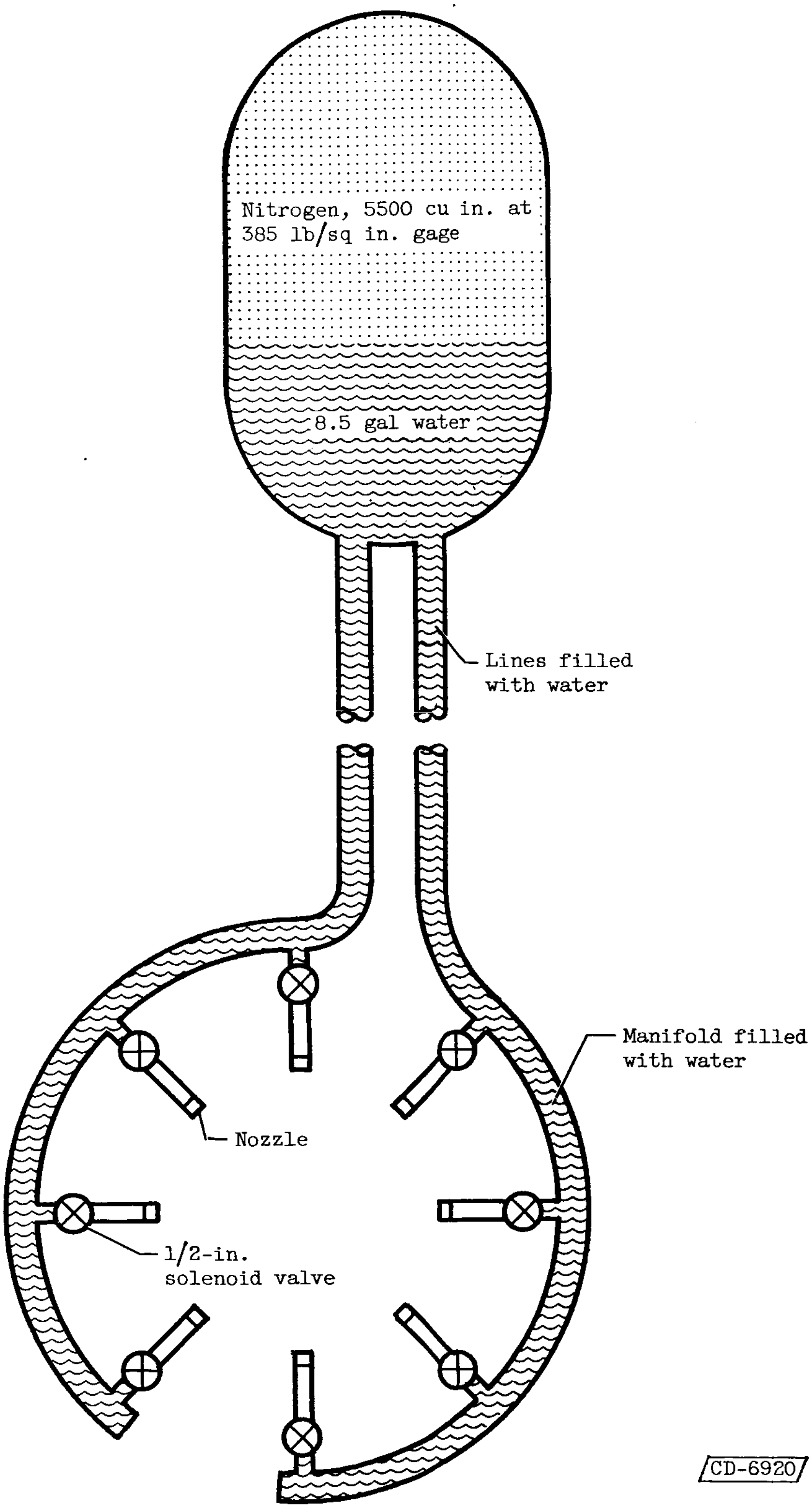
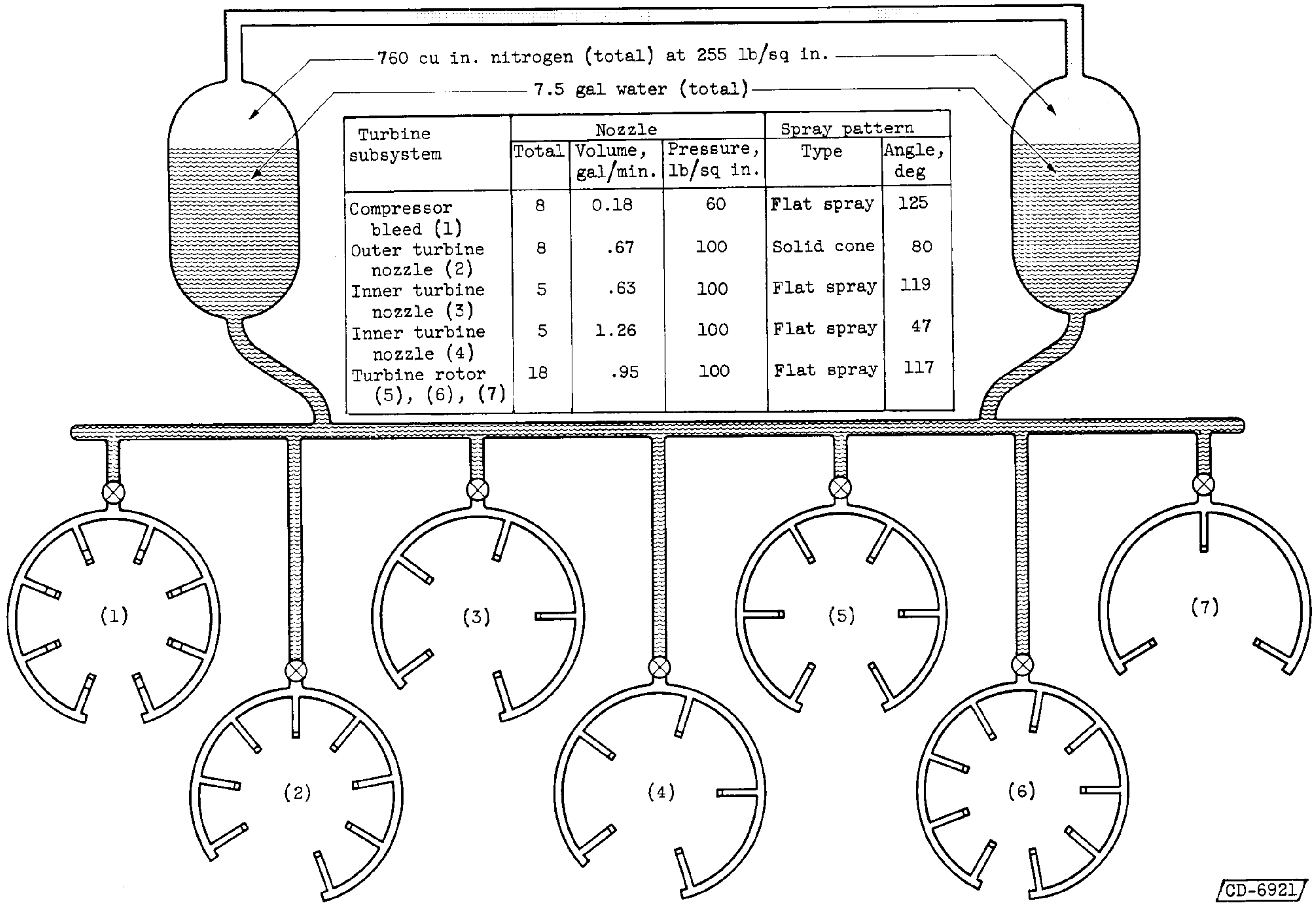


Figure 9. - Combustor system.



Turbine subsystem	Nozzle			Spray pattern	
	Total	Volume, gal/min.	Pressure, lb/sq in.	Type	Angle, deg
Compressor bleed (1)	8	0.18	60	Flat spray	125
Outer turbine nozzle (2)	8	.67	100	Solid cone	80
Inner turbine nozzle (3)	5	.63	100	Flat spray	119
Inner turbine nozzle (4)	5	1.26	100	Flat spray	47
Turbine rotor (5), (6), (7)	18	.95	100	Flat spray	117

⊗ Solenoid valve

Figure 10. - Turbine system.

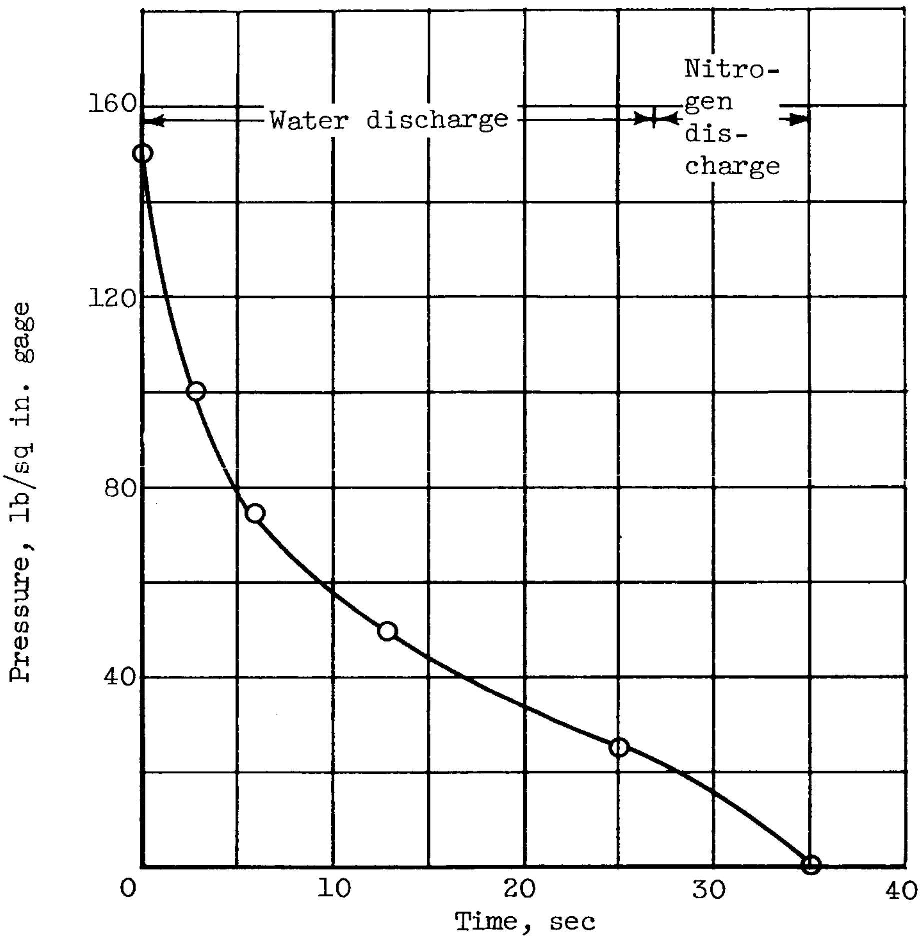
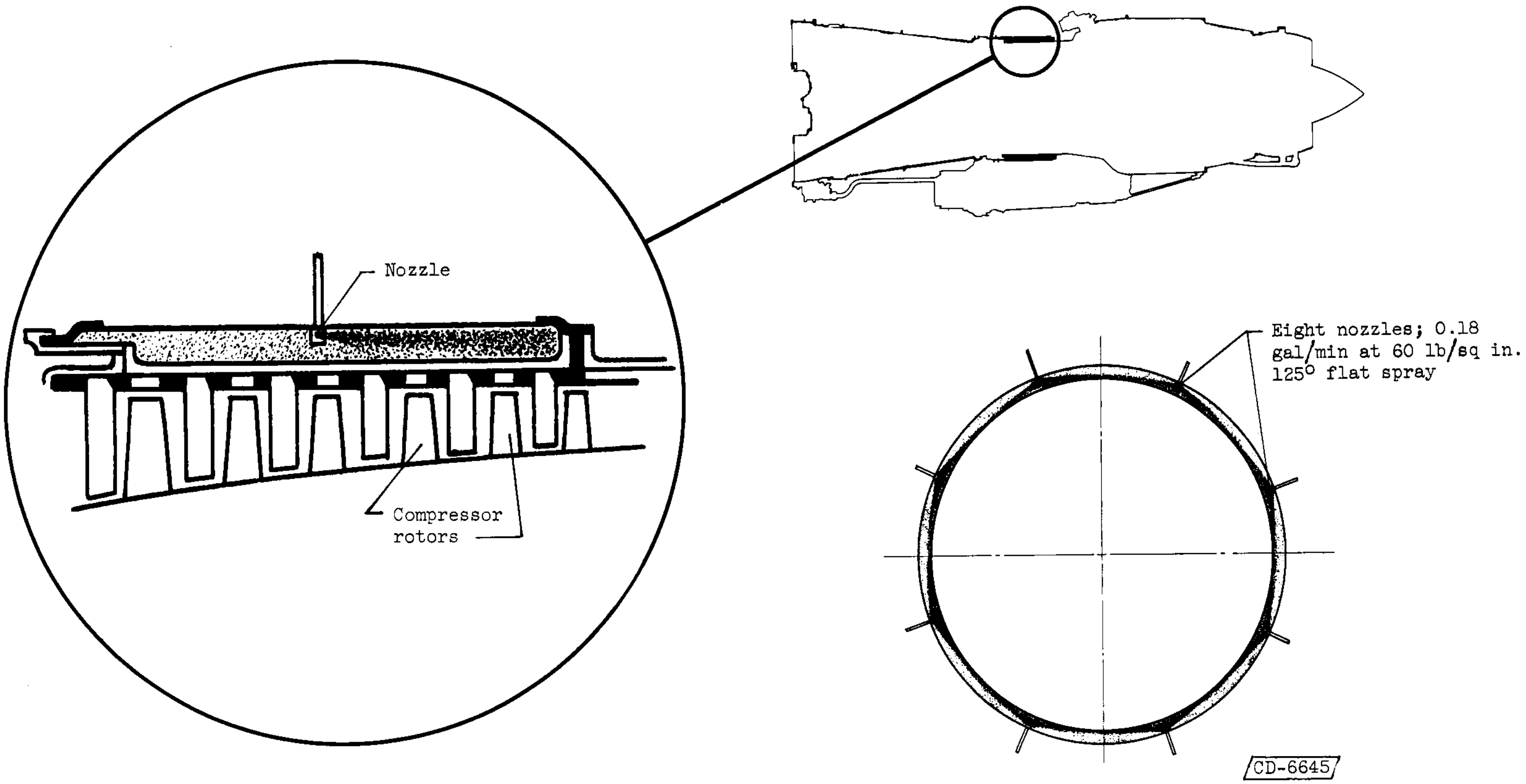
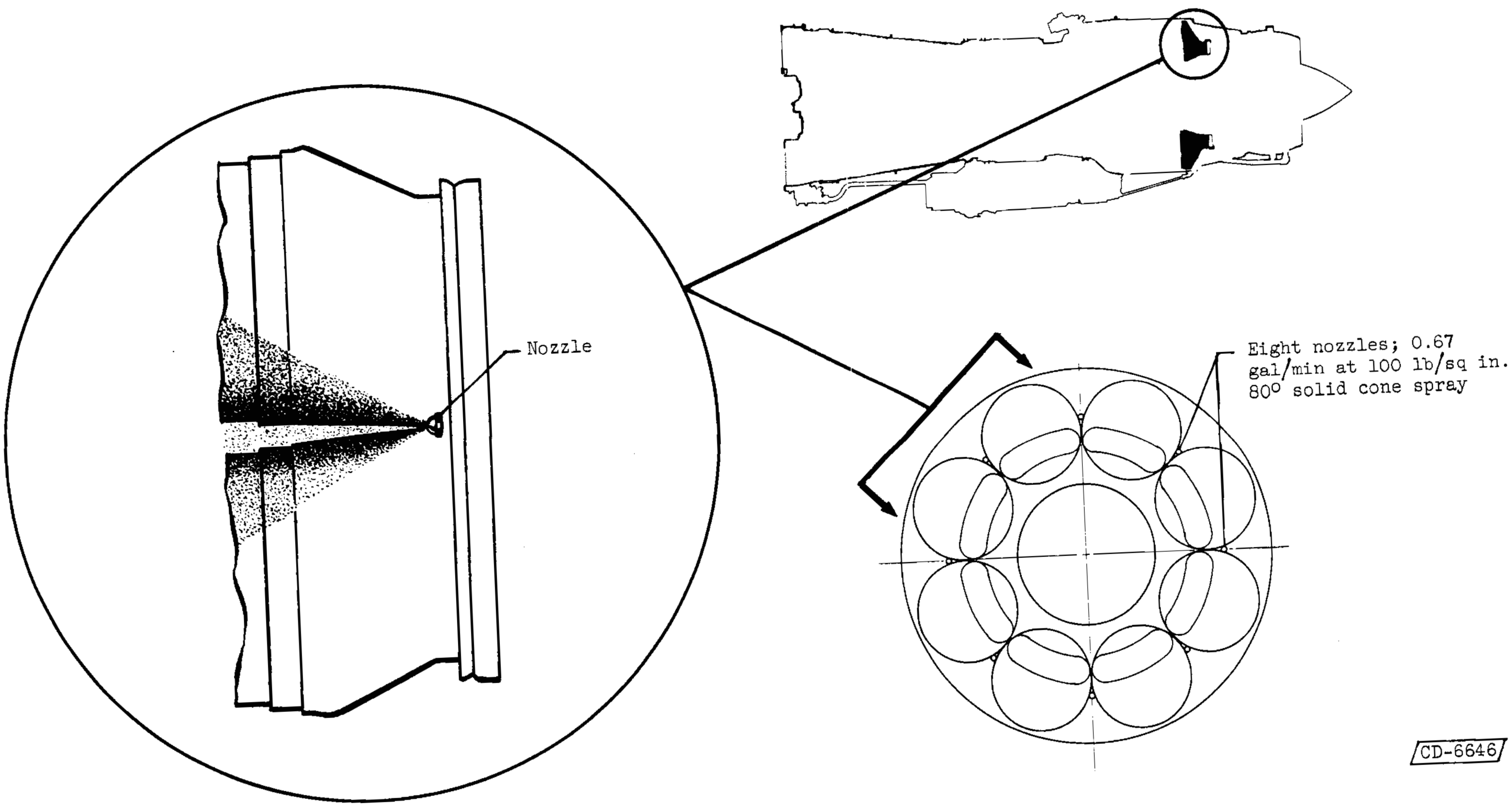


Figure 11. - Time history of crash-fire-protection combined turbine system pressure decay when discharged to atmospheric pressure (engine not operating). Water discharge, 7.5 gallons in 27 seconds.



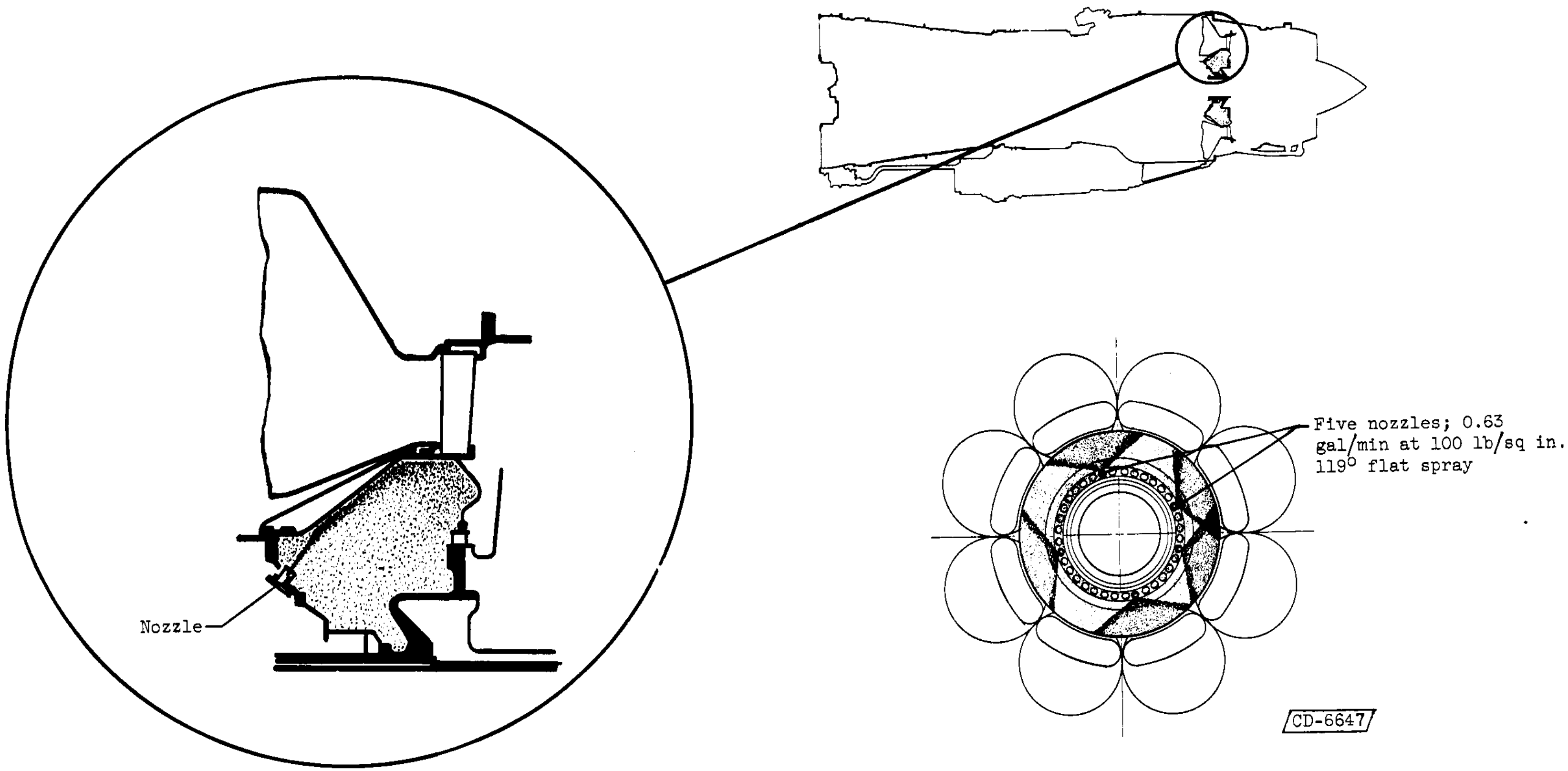
(a) Compressor bleed subsystem.

Figure 12. - Continued. Crash-fire turbine-system nozzle location in J57 engine.



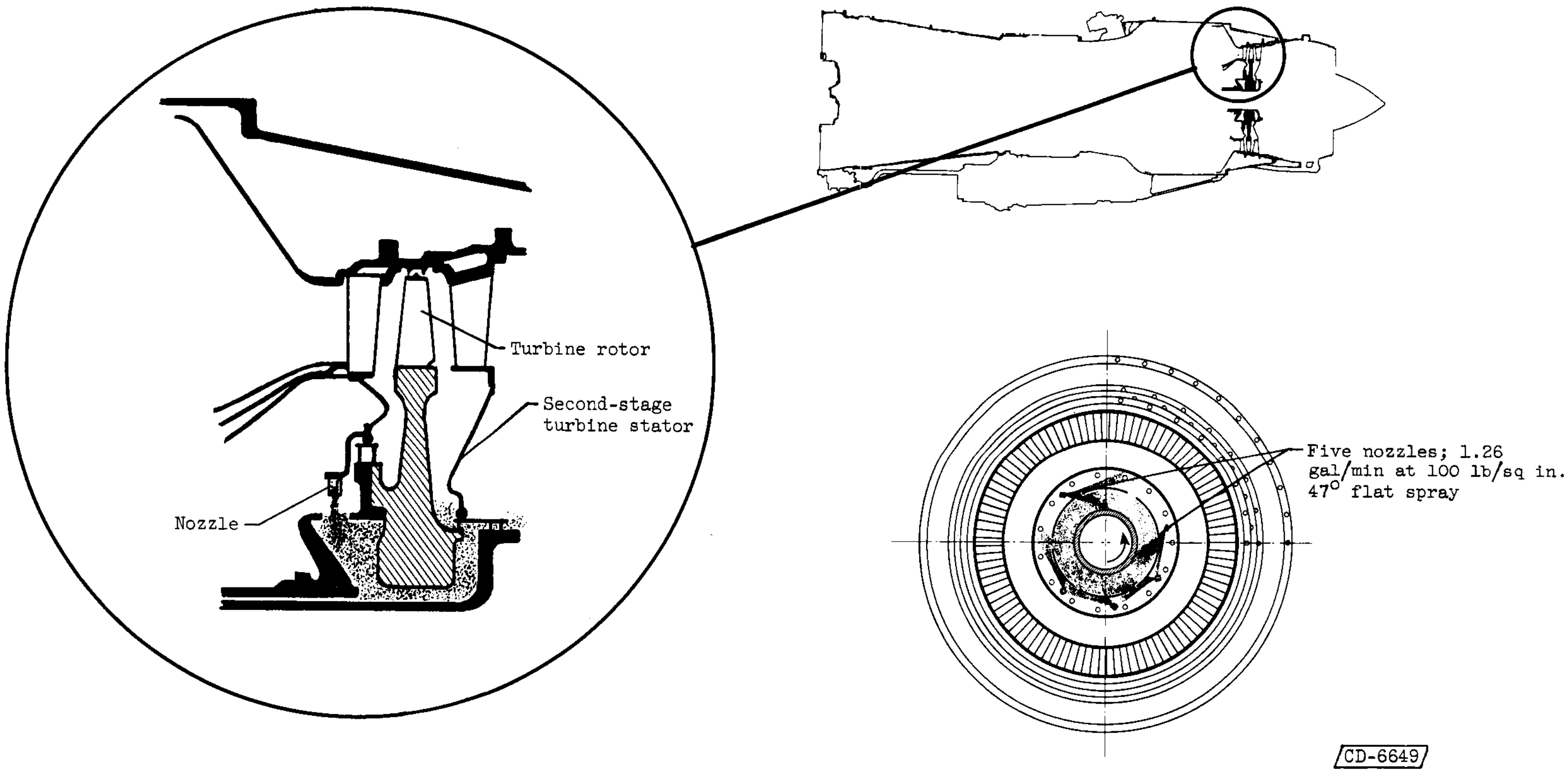
(b) Outer-turbine-nozzle subsystem.

Figure 12. - Continued. Crash-fire turbine-system-nozzle location in J57 engine.



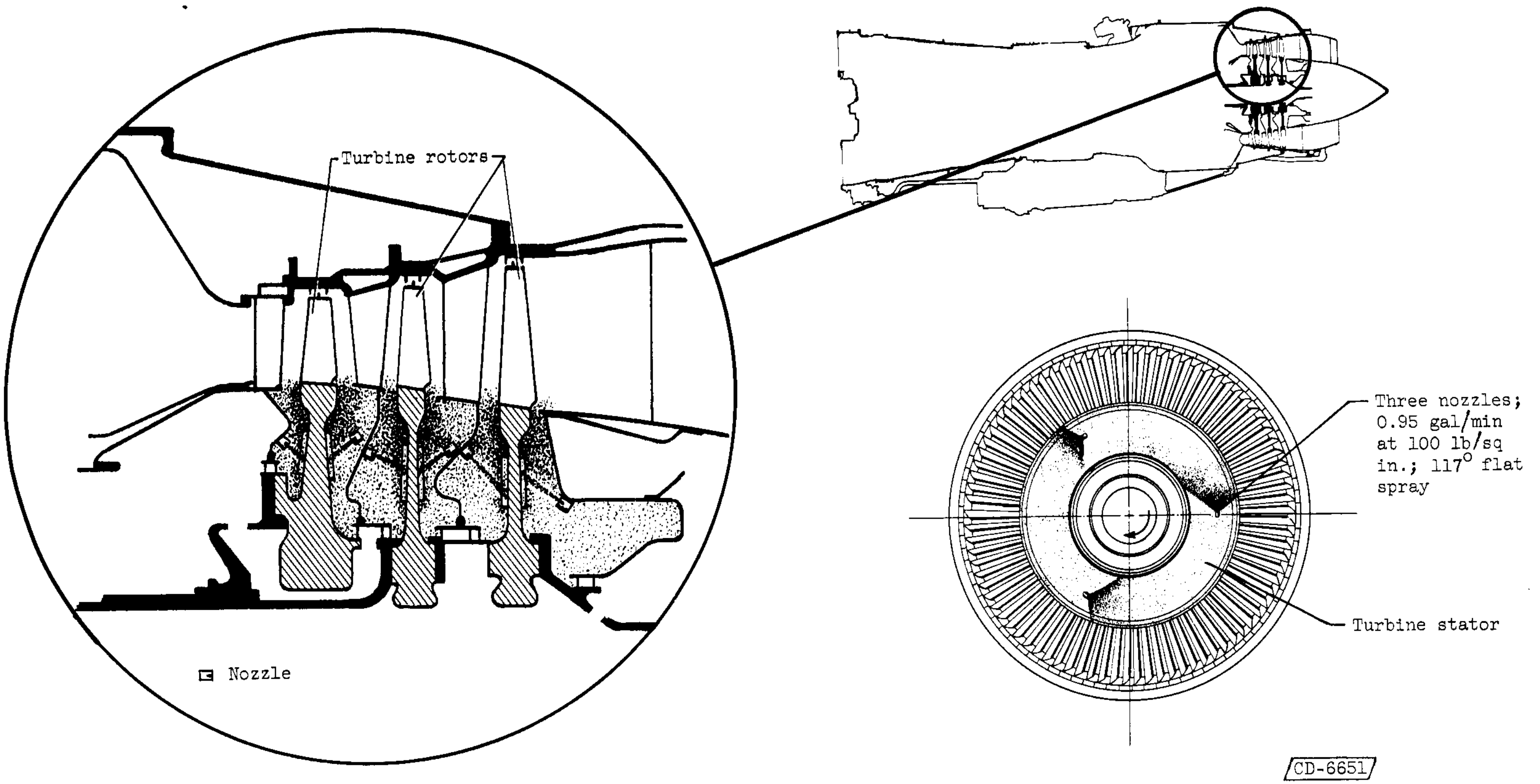
(c) Inner-turbine-nozzle subsystem 1.

Figure 12. - Continued. Crash-fire turbine-system-nozzle location in J57 engine.



(d) Inner-turbine-nozzle subsystem 2.

Figure 12. - Continued. Crash-fire turbine-system-nozzle location in J57 engine.



(e) Turbine-rotor subsystem.

Figure 12. - Concluded. Crash-fire turbine-system-nozzle location in J57 engine.

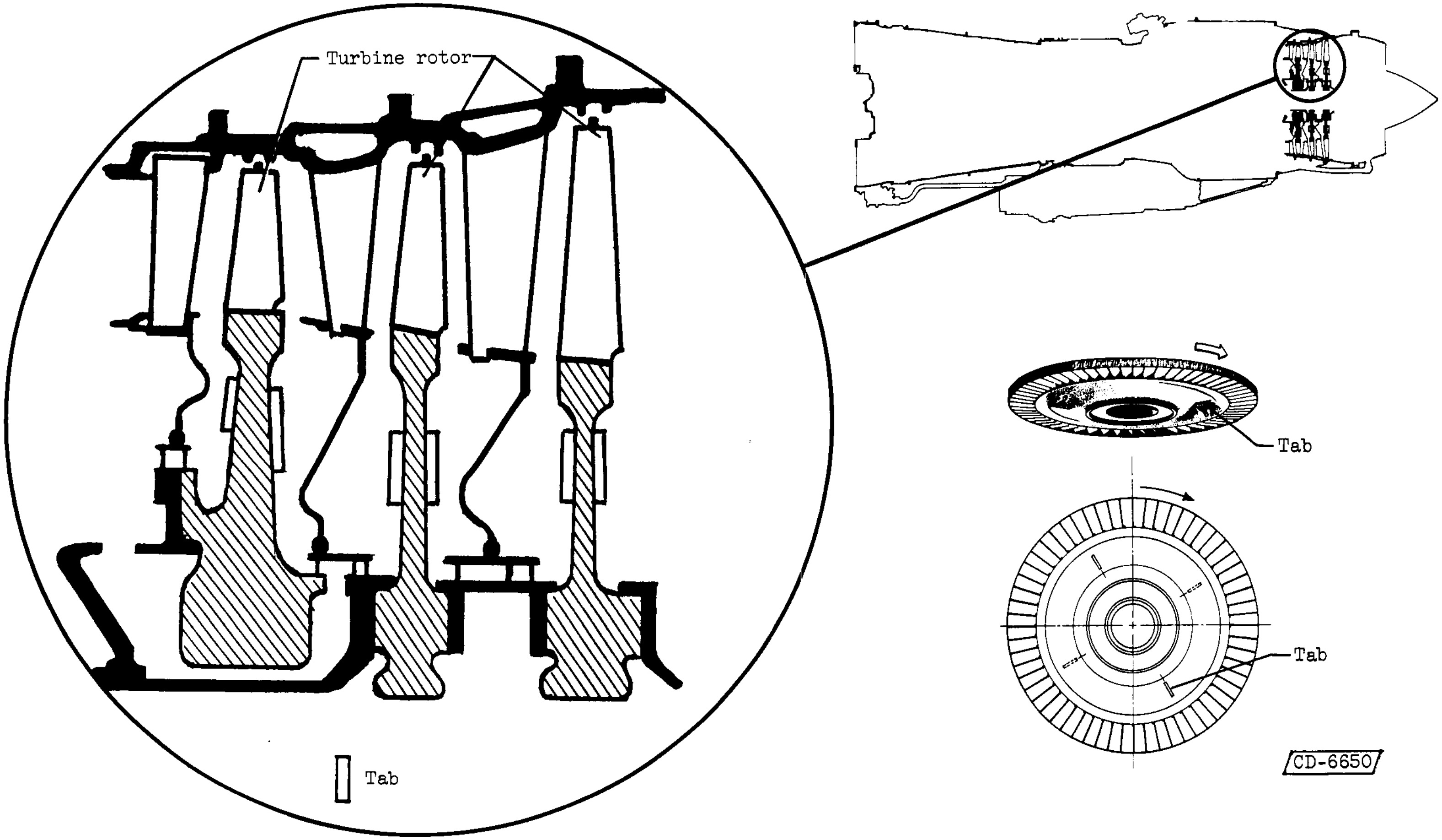


Figure 13. - Location of tabs installed on front and rear surfaces of each turbine rotor.

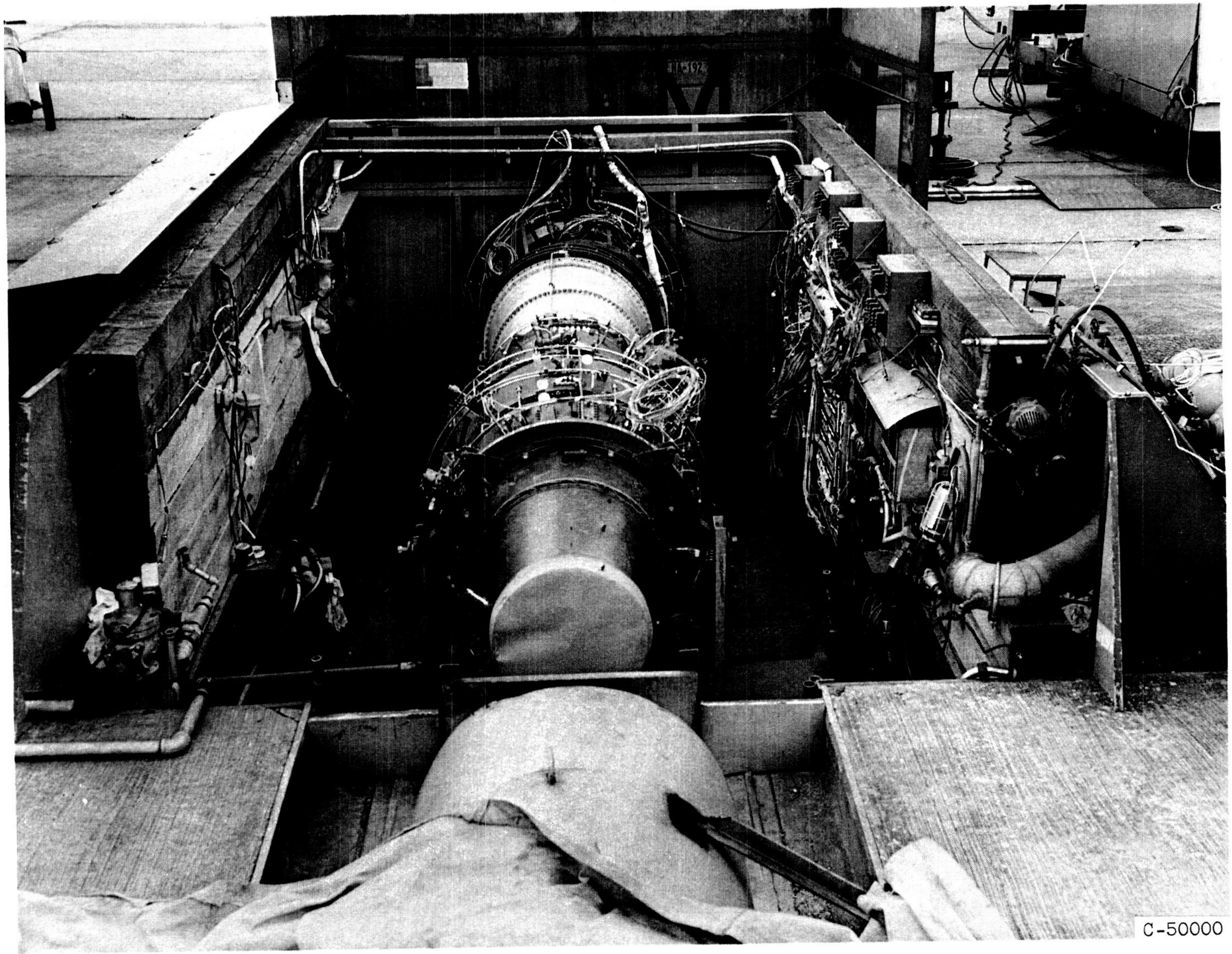


Figure 14. - Rear view of J57 engine mounted in test stand.

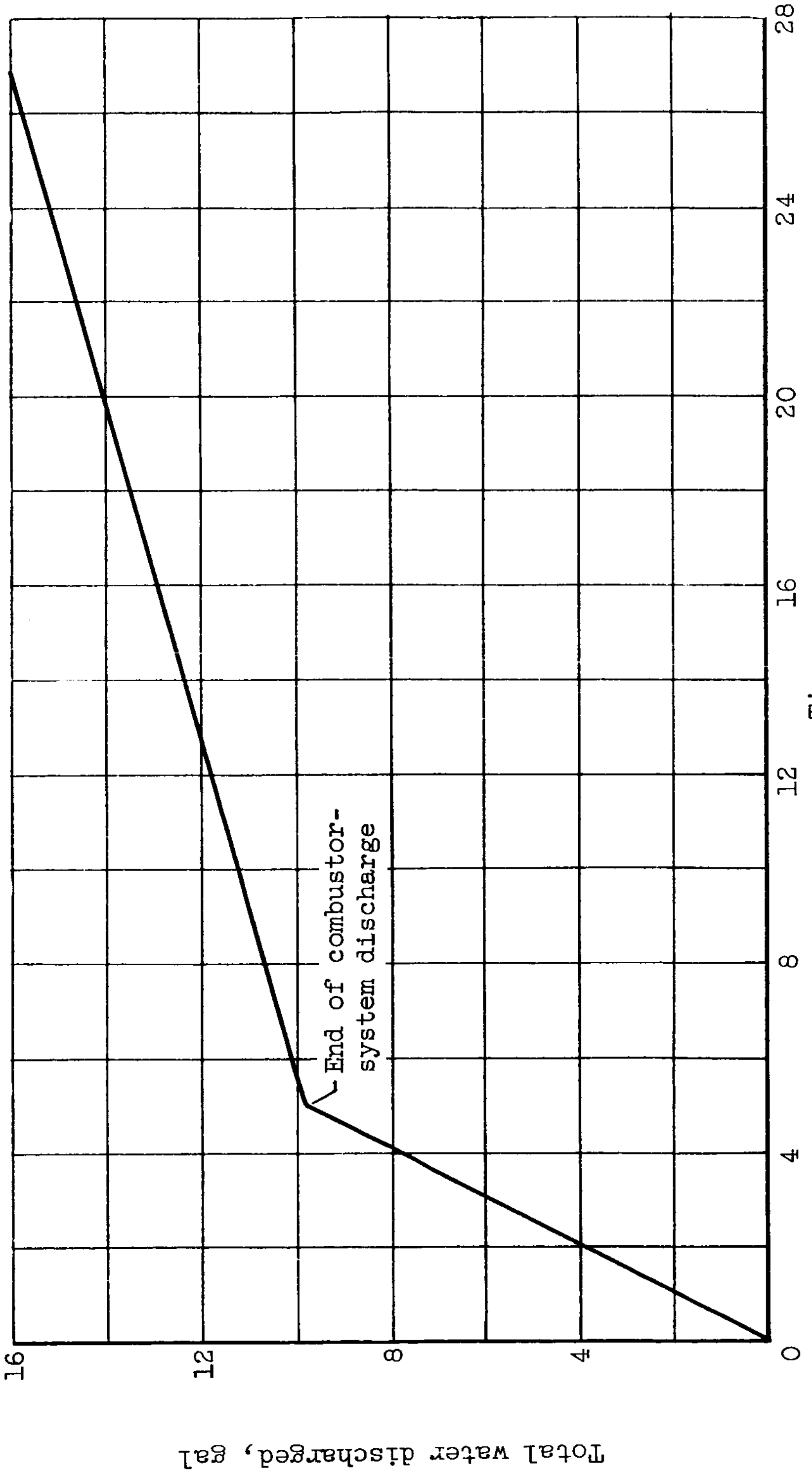


Figure 15. - Total cumulative water discharge for crash-fire-protection system.